

SECONDARY ACCELERATION OF COSMIC RAYS BY SUPERNOVA SHOCKS

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ABSTRACT

In the common model supernova shock-acceleration of cosmic rays there are two open questions: 1. where does the high energy cosmic rays below the knee ($10^4 - 10^6$ GeV) come from, and 2. are cosmic ray accelerated only at their origin or continuously during their residence in the Galaxy. We show that 10^{15} eV light nuclei are probably accelerated by associations of supernovae. The ratio of the spectra of secondary to primary cosmic rays would be affected by repeated (or secondary) acceleration in the ISM during their propagation in the galaxy. The observed secondary and primary CR spectra are used to constrain the amount of such secondary acceleration by supernova remnants (SNR). Two cases are considered: weak shocks ($1 < M < 2$) of old, dispersed remnants, and strong shocks ($M > 3$) of relatively young remnants. It is shown that weak shocks produce more secondary acceleration than what is permitted in the framework of the standard leaky box (SLB) model, making it inconsistent with dispersed acceleration that should be produced by SNR. If the SLB is modified to allow a moderate amount of RA by weak shocks, the RA produced by old SNRs agrees with the rate required to fit the secondary-to primary cosmic-ray data, making a self consistent picture. Significant secondary acceleration by strong shocks of young SNRs should lead to flattening of the secondary-to primary ratio at high energies, near 1TeV/nucleon.

WHAT IS SECONDARY ACCELERATION?

The cosmic ray spectrum in the range $1-10^5$ is probably produced by shock acceleration in the Galaxy (e.g. Axford 1981). Its power-law shape $J(p) \sim p^{2.7}$ is believed to be produced by strong shocks, probably of young SNR (Blandford and Ostriker, 1980), combined with escape from the Galaxy. After the cosmic ray particle has left the SNR site and is propagating in the Galaxy, it may encounter another SNR, be trapped and be accelerated to a higher energy. However, the probability to encounter a SNR is proportional to its volume. It turns out to be significant only for old SNR, hence with weak shocks. Indeed, Observations of the ratio of primary to secondary cosmic rays suggest such a secondary acceleration process, but at the same time constrain its amount (Eichler 1980, Cowsick 1986). Wandel et.al. (1987) have calculated the cosmic ray spectrum and the constraints on secondary acceleration set by the data under various secondary acceleration models, with the secondary acceleration amount and the shock-strength as parameters. Applying these models to RA by SNR (Wandel 1987;1988) shows that one cannot avoid secondary acceleration if one assumes that the primary cosmic rays are produced by supernovae: the young SNR producing the cosmic rays will expand and occupy a large enough fraction of the Galaxy to contribute a considerable amount of secondary acceleration. The standard leaky-box model has therefore to be modified to include RA by SNR.

BEYOND THE KNEE

Acceleration by supernova shocks can produce cosmic rays with energy up to 10^{15} eV. It is difficult to reach higher energies, because when the gyroradius of the accelerated particles becomes of the order of the shock size, the shock-acceleration mechanism cannot function, as the particle escapes. The gyroradius is given by

$$R = \frac{p}{eZB} \sim (10pc) \frac{E_{15}}{ZB(\mu G)}, \quad (1)$$

so that the maximal energy is

$$E_{15} = 0.1R(pc)ZB(\mu G). \quad (2)$$

where E_{15} is the maximal energy in units of 10^{15} eV. To reach energies beyond 10^{15} eV, larger shocks are required, and those can be obtained by going to older SNR and to associations of supernovae. Older SNR have weaker shockes, which produce a steaper power law. Indeed, a significant steepening is observed in the cosmic ray spectrum beyond 10^{15} . This could indicate that old SNR associate to produce shocked volumes of sizes of 100pc and more. With galactic magnetic fields of $3\mu G$ 100pc shocks, if abundant enough, could produce the observed cosmic ray spectrum up to $3 \cdot 10^{16}$ eV for protons and up to 10^{18} eV for iron. The formalism presented by Wandel (1988) is used to convolve the size of the SNR with teir age and shock strength, to determine the probability and rate of secondary acceleration , and the effective slope of the produced cosmic ray spectrum.

THE SECONDARY ACCELERATION MODEL

The steady state distribution of a particle population subject to contineous acceleration during its propagation is described by the integral equation

$$J_o(p) - (R + S)J(p) = B(q) \left[J(p) - (q - 1) \int_{p_o}^p \frac{dx}{x} \left(\frac{x}{p} \right)^q J(x) \right] \quad (3)$$

where J_o is the source distribution, $R = R_0(p/p_o)^{-\alpha}$ and S are loss terms due to escape from the galaxy and spallation, B is the rate of encountering accelerating events and

$$q = \frac{2M^2 + 2}{M^2 - 1} \quad (4)$$

is the index of the power law ($J \sim p^{-q}$) produced by the shock of Mach number M (q=2 for strong shocks, and larger for weaker shoks). The distribution of each secondary species satisfies a similar equation, with the source term replaced by the sum over all primary species J_i which contribute to the secondary in question, $J_s(p) = \Sigma S_{is} J_i(p)$, with S_{is} is the spallation rate from i to s, and J_i satisfies equation (3).

SECONDARY ACCELERATION AND THE LEAKY BOX MODEL

In the framework of the Standard Leaky Box (SLB) model no secondary acceleration is allowed, except the margin due to the observational uncertainties. If the SLB model is modified by allowing a modest amount of secondary acceleration (and assuming a larger escape rate, which compensates for the increase in the secondary to primary ratio caused by secondary acceleration), the constraint on secondary acceleration is less stringent. Wandel et.al. (1987) have calculated the secondary to primary (boron/carbon, denoted by B/C) energy spectrum for a modified leaky box models (MLB) with various escape laws, secondary acceleration rates and shock indices q . Their best fit of the B/C data permits a significantly larger secondary acceleration rate than in the SLB model. For shocks with $q = 4$ ($M = 1.7$)

$$\begin{cases} B < 0.03 & R_0 = 0.11 & \text{(SLB)} \\ B \approx (0.2 \pm 0.05) & R_0 = 0.2 & \text{(MLB)} \end{cases} \quad (5)$$

where B and R_0 are measured in units of inverse path length (gcm^{-2})⁻¹.

Similar constraints can be derived from the primary spectra of protons and alpha particles (e.g. Webber, Golden and Stephens 1987).

ACCELERATION BY SUPERNOVA REMNANTS

Weak shocks

The number of supernova remnants encountered by a cosmic ray particle during its residence time in the galactic disk, ($\tau_{cr} \sim 10^7 \text{yr}$ at a few GeV/nucleon) is given by $N_{cr} = \frac{4\pi}{3} r^3 S \tau_{cr} (1+C)^3$, where S is the supernova rate (per unit volume) in the galaxy, and $C = r_{cr}(t)/r$ represents the cosmic ray propagation during the remnant's lifetime. The average cosmic ray residence time in the galactic disk can be written in the form $\tau_{cr} = (1.3 c m_p n R_0)^{-1} \approx 510^5 R_0^{-1} \text{yr}$. The reacceleration rate due to supernova remnants becomes

$$B(q) = N_{cr} R_0 = 3.0 S_{12} r_{q2}^3 \left[1 + \frac{r_{cr}(t_q)}{r_q} \right]^3 = 0.14 S_{12} n^{-1} u_{q2}^{-2} (1 + C_q)^3, \quad (6)$$

where $u = dr/dt = 100 u_2 \text{km/s}$ is the shock velocity, the shock index q is related to the Mach number $M = u/c_s$ by $q(M)$ and $S_{12} = S/10^{-12} \text{pc}^{-3} \text{yr}^{-1}$ (one supernova every 30 years corresponds to $S_{12} = 0.5$). We take the sound speed in the ISM $c_s = 150 \text{km/s}$, so $M = 1.7 (q = 4)$ corresponds to $u = 250 \text{km/s}$. If the effective density seen by supernova remnants is that of the warm component of the ISM, $n_{eff} = 0.1$ (McKee and Ostriker 1977), then $r_q \sim 23 \text{pc}$, $C_q \sim 0.2 - 0.4$ (depending on the cosmic ray propagation, Wandel 1988), and eq. (6) gives $B = 0.2 - 0.4$. While this figure is by a factor 10 larger than the constraint in the SLB model, it is just the secondary acceleration rate required by the modified model in order to fit the B/C data.

Strong-Shock Secondary Acceleration by Young SNRs

The effect of secondary acceleration by young SNRs on the secondary to primary ratio has been considered in previous papers (Wandel 1990; 1991). Although the probability of encountering a young SNR is small, its effect on the cosmic ray distribution at high energies is strong, and may be detected. At high energies the solutions for the cosmic ray distribution (eq. 3) become asymptotically power laws, with the power index depending on the source acceleration index q_0 , the secondary acceleration index q , and the escape law $R \propto p^{-\alpha}$. It can be shown that the secondary to primary ratio has the asymptotic form (Wandel et.al. 1987)

$$\frac{J_s}{J_p} \rightarrow \begin{cases} p^{-\alpha} & q \geq q_0 + \alpha \\ p^{-(q-q_0)} & q < q_0 + \alpha \end{cases} \quad (7)$$

In particular, for $q = q_0$ the secondary to primary ratio should flatten at high energies. The energy at which this flattening occurs depends on the secondary acceleration rate B and on the secondary acceleration index q . From the observed cosmic ray spectra we have $q_0 + \alpha \sim 2.7$ and $\alpha \sim 0.5 - 0.6$. A significant flattening of the B/C ratio requires shocks with $q \leq 2.4$, which gives $M > 4$ and $u = 600 \text{km/s}$. Young supernova remnants may evaporate the cold phase of the ISM (McKee and Ostriker 1977), in which case $n_{eff} = 1$. If this is not the case, only the warm component is swept by the shock, so $n_{eff} = 0.1$. Finally, If the supernova expands within a cavity of hot ISM, $n_{eff} = 0.003 - 0.01$. Eq. (6) gives

$$B(q \leq 2.4) = \begin{cases} 0.003 & n = 1 \text{ (evaporation)} \\ 0.03 & n = 0.1 \text{ (no evaporation)} \\ 0.3 & n = 0.01 \text{ (hot ISM)} \end{cases}$$

If the transition between evaporative and non-evaporative expansion happens at an intermediate velocity (Cowie, McKee and Ostriker 1981), B will be between 0.003 and 0.03. The secondary to

primary (Boron/Carbon) ratio has been observed up to ~ 1 TeV by the Spacelab-2 experiment of the University of Chicago (Meyer et.al.1987). The poor statistics at the high energy end prevent a decisive conclusion. However, preliminary data suggest that the B/C ratio in the 0.1-1TeV range is approximately 0.1. Comparing this with the theoretical calculation we find that such a B/C ratio requires a secondary acceleration rate $B(q = 2 - 3) \sim 0.03 - 0.1$, so strong-shock secondary acceleration is probably important, and young supernova remnants see a relatively low effective density. Even if the B/C ratio beyond 100GeV/n is eventually found to decrease, strong shock secondary acceleration by evaporative young supernova remnants places a lower limit on the secondary acceleration rate at $B = 0.003$, which would predict a flattening near 1TeV.

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